Available online at www.sciencedirect.com
ScienceDirect
Renewable and Sustainable Energy Reviews
11 (2007) 1530–1543

RENEWABLE
& SUSTAINABLE
ENERGY REVIEWS

www.elsevier.com/locate/rser

PV hybrid systems for rural electrification in Thailand

N. Phuangpornpitak, S. Kumar*

Energy Field of Study, School of Environment, Resources and Development, Asian Institute of Technology, P.O. Box 4, Klong Luang, Pathumthani 12120, Thailand

Received 28 October 2005; accepted 23 November 2005

Abstract

Photovoltaic (PV) hybrid systems can make a positive contribution to the sustainability of rural communities in developing countries that do not have access to electricity grid. Integration of solar photovoltaic system with diesel generator for remote and rural areas would assist in expanding the electricity access in the tropical region. A survey of PV hybrid system in Thailand during the last decade regarding to status of technology, performance in terms of technical and economic aspects, and their prospects has been presented in this paper.

Keywords: PV hybrid system; Rural electrification; Technical performance; Financial analysis; Prospects

Contents

*Corresponding author. Tel.: +66 2 524 5410; fax: +66 2 524 5439.
E-mail address: kumar@ait.ac.th (S. Kumar).

1364-0321/$ - see front matter
doi:10.1016/j.rser.2005.11.008

1. Introduction

More than 1.64 billion people in the world do not have access to electricity, of whom approximately 80% live in rural Asia and Africa [1]. In Southeast Asia, about 38% of the total population does not have access to electricity. The electrification level in rural areas in South East Asia is about 51%, compared to 90% in urban areas [2,3]. In some rural areas, supply of electricity is using diesel generators. Though diesel systems have their distinct advantages of electricity generation, their operational and maintenance costs are high, especially at low loads [4–6], and storage and transportation of fuel to remote location is difficult. These systems are noisy and so not conducive for residential uses. There is also the problem of oil leakage into the streams in neighboring areas.

Application of renewable energy technologies (RETs) for rural electrification is increasing in recent years, but is not very widespread. As an option for providing power, solar photovoltaic (PV) is gaining popularity, though its high initial cost is a major barrier for its widespread use. A photovoltaic system costs about 4000$/kW, while the cost of conventional power system such as oil, gas and coal is approximately four times lower [7,8]. Thus, though PV is little far from being economic in comparison with conventional fossil fuel to provide electricity [9,10], they are used in remote areas where it is uneconomical to extend the electric grid [7,11]. However, the market for PV is also expanding rapidly due to reduced cost of PV systems during the last decade. At the same time, a PV system alone may not easily satisfy loads on 24-h basis as the variation of solar electricity generation does not always match with the time distribution of load demand [4,7,12]. The use of stand-alone wind electricity generation systems is limited in rural areas as wind resource is site dependent and depends on the season. Thus, stand alone PV or wind energy systems do not produce usable energy for a considerable portion of time during the year. PV-based hybrid system (using wind and/or diesel generator) is an option to address this barrier and supply electricity to rural areas that is far from the grid [5,6,13–17]. PV and diesel generator have complimentary characteristics. The initial cost of PV system is high compared to diesel generator, though the maintenance requirements of PV are less. However, diesel generator can provide energy at any time, whereas energy from PV is greatly dependent on the availability of solar radiation [9,11,18]. This makes the system more reliable, and can be used to operate when PV fails to satisfy the load and when the battery storage is depleted.

PV hybrid systems consist of PV arrays supplemented with battery storage and diesel generator back up or with wind energy source. Experience in operating PV/wind hybrid system is limited (Celik [19]). Protogeropoulos [6] has also noted that many problems exist arising from an increased complexity of the PV hybrid systems in comparison with single energy source systems. Particularly, the sizing of such system requires detailed analysis for a given location, the influence of various variables and their relation to the system cost, as solar radiation and wind speed are highly location dependent. Therefore, it is necessary to take into account PV and wind energy contributions to the load during the design stage.

Table 1
Summary of PV hybrid system in operation or under development of Thailand

Location of sites/application areas and responsible agency	Description/capacity	Installation date	Cost
1. Promthep Cape, Phuket • Demonstration of renewable energy • EGAT	• PV/wind hybrid system • 10 kWp PV array • 170 kW wind turbine	Grid connected since September 1990	Installation: 12,350,000 Baht [37,38]
2. Tha Takiab, Cha-Choeng Sau • Demonstration of PV/wind/diesel hybrid unit • Provision of electricity for a wildlife research station • KMUTT	• PV/wind/diesel hybrid system • 1.1 kWp PV array • 0.8 kW wind turbine • 3 kW diesel generator	In operation since August 1995	Installation: 1,410,000 Baht [39]
3. Kirimas, Sukothai • Provision of electricity for offices and visitor lodges at Ram Kham Haeng National Park • KMUTT	• PV/diesel hybrid system • 2 kWp PV array • 5 kW diesel generator	In operation since November 1995	Installation: 800,000 Baht [39]
4. Watpa Terdprakiat Sirindhorn, Loei • Provision of electricity for the remote temple • KMUTT	• PV/diesel hybrid system • 1.9 kWp PV array • 5 kW diesel generator	In operation since 1996	Donation to the temple
5. Huai Kha Khaeng, Uthai Thani • Provision of electricity for offices and visitor lodges at Huai Kha Khaeng Wildlife Sanctuary • KMUTT	• PV/diesel hybrid system • 10.5 kWp PV array • 42 kVA diesel generator	In operation since July 1998	*Total cost*: [21] Installation: 5,573,247 Baht Replacement: 2,703,772 Baht O&M: 86,131 Baht/year *Benefit:* Fuel saving: 69,258 Baht/year O&M saving: 2488 Baht/year
6. Tarutao, Satun • Provision of electricity for offices and visitor lodges at Tarutao National Park • KMUTT	• PV/wind/diesel hybrid system • 7.5 kWp PV array • 10 kW wind turbine • 48 kVA diesel generator	In operation since April 1999	*Total cost*: [21] Installation: 7,462,701 Baht Replacement: 4,002,744 Baht O&M: 125,904 Baht/year *Benefit:* Fuel saving: 115,430 Baht/year O&M saving: 2445 Baht/year

Table 1 (*continued*)

Location of sites/application areas and responsible agency	Description/capacity	Installation date	Cost
7. Phu Kradung, Loei • Provision of electricity for offices and visitor lodges at Phu Kradung National Park • KMUTT	• PV/wind/diesel hybrid system • 7.5 kWp PV array • 2.5 kW wind turbine • 42 kVA diesel generator	In operation since May 1999	*Total cost*: [21] Installation: 7,350,679 Baht Replacement: 3,108,847 Baht O&M: 106,624 Baht/year *Benefit:* Fuel saving: 65,960 Baht/year O&M saving: 1613 Baht/year
8. Doi Intanon Royal Project, Chiang Mai • Provision of electricity to mountainous villager 510 households/ 2,793 users • KMUTT	• PV/diesel hybrid system • 0.6 kWp PV array • 5.25 kVA diesel generator	In operation since 2002	Installation: 329,782 Baht [39] O&M: 476 Baht/year
9. Wat Chan Royal Project, Chiang Mai • Provision of electricity to mountainous villagers • KMUTT	• PV/diesel hybrid system • 0.6 kWp PV array • 5.25 kVA diesel generator	In operation since 2002	Installation: 329,782 Baht [39] O&M: 476 Baht/year
10. Kohjig, Chantaburi • Provision of electricity to islanders • KMUTT	• PV/wind/diesel hybrid system • 7.5 kWp PV array • 10 kW wind turbine • 65 kVA diesel generator	In operation since November 2004	*Total cost*: [25] Installation: 7,750,428 Baht Replacement: 7,305,060 Baht O&M: 281,820 Baht/year *Benefit:* Fuel saving: 140,070 Baht/year Medical benefit: 30,000 Baht/year

Many PV-based hybrid systems have been installed in Thailand in recent years. This paper analyses the PV hybrid systems installed in Thailand: PV/wind hybrid system, PV/diesel hybrid systems, and PV/wind/diesel hybrid systems for rural electrification. The analysis of these systems focuses on the types of systems used, status of technologies, performance of the systems in terms of technical and financial, and discusses the prospect of such systems.

2. Status of PV hybrid system in Thailand

A survey of PV hybrid system installed in Thailand during the last decade is presented in Table 1. The table presents details of the sites, application areas, description of the systems, and the installation and cost details. It comprises small PV hybrid systems with diesel generators rating only few kilowatts, to large systems with diesel generators of tens of kilowatts capacity.

2.1. System size and applications

A total of about 40 kWp by PV modules, 23.2 kW by wind turbines and 220.5 kW by diesel generators have been installed with a total initial capital outlay of about approximately 31 million Baht. These off-grid connected systems are installed in remote and rural areas. All the PV systems installed use single crystalline PV cells. More than 60% of these systems were installed in national parks and wildlife sanctuaries, where these systems provided electricity for offices and visitor's lodges. About 30% were installed in isolated islands for provision of electricity to islanders, and the rest were installed in mountainous villages and a remote temple.

The electricity supply of PV hybrid systems in rural areas of Thailand range about 10–220 kWh/day, and this type of applications appears to be cost-effective especially when utilize for rural electrification. Turcotte and Sheriff [20] have also noted that PV hybrid systems are generally cost-effective for small loads of typically less than 40 kWh/day.

2.2. System cost details and organizations involved

Most PV hybrid systems were installed through the cooperation of King Mongkut's University Technology Thonburi (KMUTT), the Provincial Electricity Authority (PEA) and the Electricity Generation Authority of Thailand (EGAT). The systems were funded by the Energy Policy and Planning Office (EPPO), though the communities were responsible for operation and maintenance of the system.

The costs of the systems depend on size, location, customer type and technical specification. The costs of grid-connected systems amounts to about 70 Baht/Watt,[1] stand-alone systems costs are about 95–140 Baht/Watt (Table 1).

3. Performance

The performances of PV hybrid systems are discussed under technical and financial aspects.

3.1. Technical performance

In Thailand, PV hybrid systems were installed as pilot projects since 1990. Most of them were adapted for national parks and wildlife preservation areas or rural villages that do not have access to electricity. Nine off-grid PV hybrid systems ranging from 5 to 82.5 kW, with a total installed capacity of about 285 kW, are in operation and constitute about 10% of the total PV power installed in Thailand. Although these systems have been monitored since their

[1] 1US$ = 40 Baht approximately (September 2005).

installation, operational data sets and maintenance information are available only for few such systems. In particular, overall energy production and utilization, system efficiency, as well as specific problems for PV hybrid systems installed in Huai Kha Khaeng wildlife sanctuary, national parks of Tarutao and Phu Kradung, and remote island of Kohjig will be described.

3.1.1. *Wildlife sanctuary*

The first hybrid power system in a wildlife sanctuary, Huai Kha Khaeng, was set up by KMUTT in 1998 with the aim to assess technological, economical and operating aspects and to study the penetration of PV in remote and preserved areas. During 1998–2003, the system supplied 44,504 kWh (PV supplying about 88.5% of the total demand) or an average of 24 kWh/day. This was, however, lower than the designed value (rated at 30 kWh/day) [21]. The analysis of the performance of this system, shown in Fig. 1, indicates that the average solar radiation during 1998 was 4.0 kWh/m^{2}day, which was less than the design data (set at 4.5 kWh/m^{2}day), which probably was one cause in the reduction of PV-generated power [22].

The PV/diesel hybrid system installed at Huai Kha Khaeng wildlife sanctuary in 1998 was optimized to meet current and changing demand for a clean and reliable power source. The system can supply electricity to load because the diesel generator works to compensate any inconvenience caused by photovoltaic [23].

3.1.2. *National park*

PV/wind/diesel hybrid systems were installed in 1999 at Phu Kradung, a high-elevation national park in Loei Province, and at Tarutao, an island in a marine national park in Satun Province, Thailand. The overall energy production and utilization at both these national parks do not provide the best possible match with PV output since these loads typically peak during the early morning and evening hours as shown in Fig. 2. An analysis of the system parameters indicates the following [24]:

- The overall system efficiency, defined by the product of the mean array efficiency and the efficiency with which the energy from all sources is transmitted to the loads at Tarutao was 9.5% and at Phu Kradung, it was 9.7%.

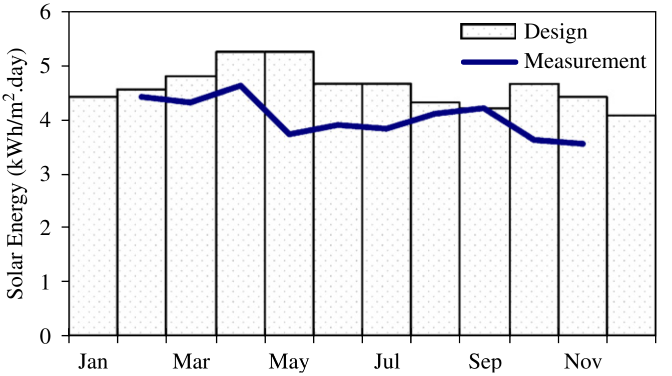

Fig. 1. Comparison between actual and design solar radiation data for Huai Kha Khaeng wildlife sanctuary (KMUTT, 2004).

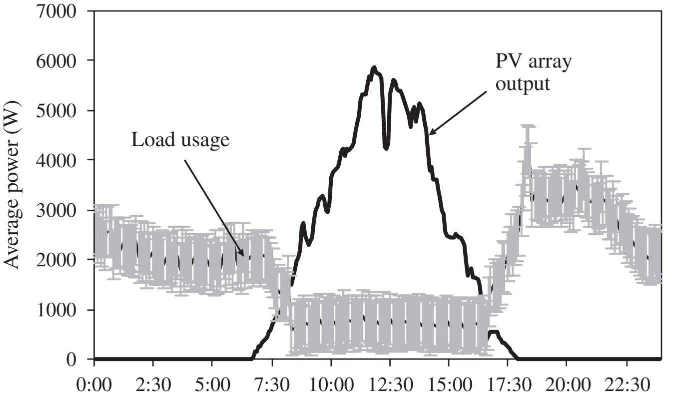

Fig. 2. Daily load pattern and average PV output at Tarutao national park (KMUTT, 2004).

- The PV array efficiency was 9.0% at Tarutao, while it was 8.5% at Phu Kradung.
- The average battery efficiency of both hybrid systems was about 88.5%, which is slightly lower than that of design (compared to the design value at charging rate 60%, the battery efficiency was 90%). This is due to the share of battery distribute energy to the load was higher in practical and this shortened the battery life.
- The PV and wind turbine contribute the dominant part of the electricity (about three quarters) in both the hybrid systems and the system subunits function as designed.

The hybrid system at Phu Kradung national park could not satisfy the requirements during the peak period of tourism (December–January), when the load was about 36 kWh/day that was significantly higher than its design (24 kWh/day) [21]. The causes for this were lack of information advocacy on hybrid energy system to the tourists and institutional issues (e.g., frequent change of officials at the national park). This resulted in using more diesel to supply the high load than its design (760 l/year) to operate the diesel engine. In 2001, the operational hour of diesel engine was 240 h (compared to the designed 160 h/year) and use of diesel fuel was about 1140 l/year.

3.1.3. Remote island

The hybrid system at Kohjig in Chantaburi Province was aimed at testing innovative components and advanced systems, and to gather experience in construction and operation on large scale PV hybrid system to provide electricity to the islanders [25]. A combination of 10 kW wind turbine generator and 7.5 kWp PV array satisfies about 27% load. The remaining energy required to match the load was by the diesel generator, about 73%, which required fuel consumption 36,054 l/year.

The Kohjig system started to operate at the end of 2004. During the subsequent 8 months, energy production has been inferior than expected due to problems with components e.g. fuses blown and wires connecting to the controllers got disconnected. Most of the problems were solved locally either by the users or by the technician. Technician and users training were found to be effective in performing local maintenance and repair works. User training has helped to carry out the required maintenance of the

system e.g. cleaning module surface, replacing fuses and adding distilled water to the battery.

PV hybrid systems installed at Huai Kha Khaeng wildlife sanctuary and those at Tarutao and Phu Kradung national parks have shown good system efficiency and overall plant efficiency confirming their design values. Other systems (Kohjig) have instead shown lower reliability mainly due to partial failure of the system.

3.2. Financial performance

Most PV hybrid systems in Thailand have been installed in national parks and wildlife sanctuary for provision of electricity to offices and visitor lodges. At national parks, (Phu Kradung, a high-elevation national park in Loei Province and Tarutao, an island in a marine national park in Satun Province), these systems replaced the diesel generators. The overall cost analysis, cost structure of each component and financial indices will be addressed in this section.

The economic analysis to determine the overall feasibility of the systems installed at two national parks, Tarutao and Phu Kradung, are shown in Tables 2–4. During the operation of these systems during 1999–2000, data such as the annual energy consumption, fuel consumption, operation and maintenance cost were collected and shown in Table 2 [21]. A detailed cost analysis, taking into account initial cost and annual cost, was conducted using HOMER computerized assessment tool (version 2.09) developed by the National Renewable Energy Laboratory (NREL). The following assumptions were used:

- Using the design of hybrid energy system proposed by Markvart [26] and El-Hefnawi [27], the energy demand of 36 kWh/day and 24 kWh/day was used for Tarutao and Phu Kradung national parks, respectively.
- Since no record of the meteorological data (i.e., solar radiation, wind speed and ambient temperature, etc.) at the site was available, the data from the nearby meteorological station about 20 km away was taken for the design.

At Tarutao national park, the results from HOMER indicates an annual operation cost of 20,070 Baht, with the annual fuel usage of 1338 l. In Phu Kradung national park, the annual operational cost is estimated at 17,100 Baht, using 1140 l of fuel. 15 Baht/l was used as an average fuel cost for calculation.[2] The initial investment of these systems was about 7.5 million Baht. The benefit cost was calculated and compared between the PV hybrid system and the diesel system alone [19,28]. The hybrid system can reduce the operational hours of diesel engine, presenting a significant cost saving of fuel and maintenance [29].

The annual maintenance cost estimated as a percentage of each component cost is shown in Table 3. For example, the maintenance cost for PV array is 0.005 times PV array cost, 0.02 times controller cost and 0.03 times battery cost [21,25]. Seventy percent of maintenance cost for both sites is for the battery and inverter.

Table 4 shows the cost structure, comparing the share of electricity produced by each component. The PV component cost share is slightly greater than 20% in the three sites. However, this PV component cost doubles in Huai Kha Khaeng wildlife sanctuary because this site has two power generators compared with others that have three power generators.

[2]The fuel cost in September 2005 is 23 Baht/l.

Table 2
Summary of cost analysis of the two national parks [21]

Parameters	Tarutao	Phu Kradung
System size	7.5 kWp PV array 10 kW wind turbine 48 kVA diesel generator	7.5 kWp PV array 2.5 kW wind turbine 42 kVA diesel generator
Initial cost (Baht)		
Investment cost	7,462,701	7,350, 679
Annual cost (Baht per year)		
Operating cost	20,070	17,100
Management cost	105,834	89,524
Benefit (Baht per year)		
Fuel saving	115,430	65,960
Maintenance saving	2445	1631

Table 3
Maintenance cost analysis of the two national parks [21]

No	Component	Lifetime (year)	Maintenance cost (times) (A)	Tarutao		Phu Kradung	
				Component cost (Baht) (B)	Maintenance cost (Baht) ($C = AB$)	Component cost (Baht) (D)	Maintenance cost (Baht) ($E = AD$)
1	PV array	20	0.005	1,650,000	8250	1,650,000	8250
2	Wind turbine	10	0.010	902,879	9029	344,026	3440
3	Inverter	10	0.030	1,005,132	30,154	670,088	20,103
4	Battery	5	0.030	1,346,400	40,392	1,346,400	40,392
5	Controller	10	0.030	458,333	9167	458,333	9167
6	Battery charger	10	0.030	140,000	4200	140,000	4200

The share of the battery cost to total cost varies from 18.3% to 30.2% due to its capacity and price, and inverter and controller cost constitutes around 10% of total cost in Kohjig, and 20% in other places. Reduction of the share of inverter and controller cost is reflected by technology advancement in the balance of system components [30].

Structure and miscellaneous cost includes logistics, transportation and labor cost, and this depends on site. In Phu Kradung national park, this cost seems to be 10% higher (25% higher in case of Huai Kha Khaeng wildlife sanctuary) than others, as this park is located in hilly area and so the logistics/transportation cost is higher. Wind generator cost is higher in Tarutao due to its favorable location of the island, and its capacity is larger.

A detailed analysis includes the following main categories: financial parameters, project cost and saving, financial feasibility and yearly cash flow [31]. The economic index which

Table 4
The cost structure of each component (% total cost)

Location of sites (installation date)	PV power generation				Wind power generation	Diesel generator
	PV	Battery	Inverter/ controller	Structure and miscellaneous[a]		
Huai Kha Khaeng Wildlife Sanctuary (Jul 1998)	41.4	24.2	21.6	12.8	—	n/a
Tarutao National Park (Apr 1999)	22.1	18	21.5	26.3	12.1	n/a
Phu Kradung National Park (May 1999)	22.4	18.3	17.2	37.4	4.7	n/a
Kohjig (Nov 2004)	23.1	30.2	11.9	24.2	3.6	7.0

n/a—it implies that the location already possesses the diesel generator.
[a]Structure of PV panel and battery, control building, transportation cost.

indicated the benefits of these system are given in term of Net Present Value (NPV), Benefit Cost Ratio (B/C), Internal Rate of Return (IRR), and Payback period. In addition, the criteria for analyzing an appropriate system to install renewable energy in remote areas is considered by the available resource for producing electricity, operation and maintenance the system, and the Economic Internal Rate of Return (EIRR) for that area [28]. Table 5 summarizes the results. The hybrid system at Tarutao national park was worthwhile in terms of the return on investment as the NPV (205,505 Baht) was positive and the EIRR (15.5%) was greater than the interest of the loan used for the investment. Upon completion of the system, the benefit gained from the system was higher than the cost by 205,505 Baht.

On the other hand, at Phu Kradung national park the PV/wind/diesel hybrid system was not worthwhile in terms of the return on investment as the NPV (−1,540,312 Baht) was negative and the EIRR (9.9%) was lower than the interest of the loan used for the investment. Upon completion of the system, the benefit gained from the system was lower than the cost by 1,540,312 Baht. This is mainly because of the over design of the system. The available solar radiation and wind speed during the study period were less than the design data and energy demand was more than design data. Actual hours of operation of the diesel generator were more than the assumptions used. However, when environmental externalities are added, the return on investment was higher as the NPV (6,576,163 Baht) was positive and the EIRR (33.8%) was greater than the interest on the loan used for the investment [33,34].

From these results, it can be observed that the PV/wind/diesel hybrid system installed at Tarutao national park provides the best case even excluding the addition of environmental externalities. In terms of environmental impacts, PV does not produce any pollution. Hybrid system will bring more environmental benefits than conventional power in terms of human health, reduction of air pollution and decrease of noise etc. However, in the above estimation, these were not considered.

The analysis shows that remote area power systems using renewable energy sources optimized with diesel generator back up can be economically attractive, particularly when environmental benefits are used in the calculation. Environmental benefits may include human health improvement, air pollution decrease, noise reduction, etc.

Table 5
Financial indices of the two systems [21]

Financial indices	Tarutao	Phu Kradung
NPV (Baht)	205,505	−1,540,312[a]
IRR (%)	5.76	3.08
Payback period (years)	5.7	7.9
B/C ratio	5.3	4.7

[a]When environmental externalities were included, the return of investment was much higher as the NPV (6,576,163 Baht) was positive.

4. Prospects in Thailand

Thailand is now the largest PV user in Southeast Asia. By 2006, Thailand would have installed approximately 50 MW [32]. In the last decade, many PV hybrid systems have been installed at national parks, wildlife sanctuaries and remote villages in island and mountainous areas, which indicates an increasing interest PV hybrid system for decentralized applications. According to the National Energy Plan of Thailand, 8 MW PV hybrid systems would be installed in remote areas [33]. The criteria for choosing an appropriate system to install the renewable electrification in remote areas are the resource availability (solar/wind) for producing electricity, conduciveness for the operation and maintenance of the system, and costs [11].

The survey carried out by PEA in the various islands in 2001 [34,35] indicates that there are 36 communities that do not have any access to electricity. Of these remote islands which plan to install PV hybrid systems are Koh Mak Noi and Koh Pan Yi in Phangnga, Koh Sin Hai in Ranong and Koh Yao in Satun. For these islands the most suitable power generation appears to be a combination of PV and diesel hybrid system [34]. Based on the surveys, details of design, capacities of systems and capital costs, have been estimated and are summarized in Table 6. The initial cost of these four systems ranges from 8 to18 million Baht, with the least cost at Koh Yao and the highest at Koh Pan Yi. Sixty percent of total PV capacity planned to be installed will be at Koh Pan Yi and Koh Mak Noi, while the capacity of diesel engine would range from 40 to 310 kW. In islands where villages are distant from each other, central generation for each village would be preferred [36].

Key factors for sustaining PV hybrid systems are technical training and community participation. Training, education and information dissemination to the users is a major factor contributing to successful system operation. Community participation plays an important role for sustaining PV hybrid system rural electrification schemes. This can result, for example, in:

- Involvement of local authority in decision making on the type of power generation to be installed in their community.
- Providing training on maintenance, operation and handling of the specific power generation for those who are in charge of the system.
- Ownership of the systems by villagers; however, for national parks local officials should be responsible for the system.

Table 6
Capacity and capital expenditure [34]

No.	Island	Population	PV (kW)	Diesel generator (kW)	Total initial cost[a] (Baht)
1	Koh Mak Noi	1243	20	2×60	13,417,162
2	Koh Sin Hai	548	25	2×25	11,999,047
3	Koh Yao	666	15	1×15 1×25	8,208,479
4	Koh Pan Yi	1500	40	1×60 1×250	18,051,535

[a]Total initial cost excluding cost of diesel generator since the villages already possess diesel generator.

5. Conclusion

The combination of renewable energy sources such as PV or wind with diesel generator appears to find increasing appeal in implementing decentralized electricity generation systems for remote areas. The addition of a diesel generator to the renewable energy system provides power on demand, improves reliability and reduces the initial cost of the system. Similarly, renewable energy addition to a conventional fossil fuel operating diesel generator reduces fuel consumption, thus improving the economics and environmental attributes of the power source. It can be applied to various geographical conditions, mountainous, island or plain areas, where electricity is not available.

A review of the overall energy production and utilization as well as the system performance of PV hybrid systems in Thailand indicates the promising potential of such systems in the future.

Acknowledgments

N. Phuangpornpitak is grateful to the Energy Policy and Planning Office, Thailand for the financial support in conducting this study. She would also like to extend her sincere thanks to Pilot Plant Development and Training Institute, King Mongkut's University of Technology Thonburi and Provincial Electricity Authority, who provided data for this study.

References

[1] GNESD. Improving energy access, the possibility contribution of RETs to poverty alleviation. In: International conference for renewable energies. Bonn, Germany, 1–4 June 2004.
[2] IEA, Energy Outlook 2000–2030. International Energy Agency, Paris; 2002.
[3] Shrestha RM, Kumar S, Sharma S, Todoc MJ. Institutional reforms and electricity access: lessons from Bangladesh and Thailand. Energy for Sustainable Development 2004;8(4):41–53.
[4] Nayar CV, Phillips SJ, James WL, Pryor TL, Remmer D. Novel wind/diesel/battery hybrid energy system. Solar Energy 1993;51(1):65–78.
[5] Elhadidy MA. Performance evaluation of hybrid (wind/solar/diesel) power systems. Renewable Energy 2002;26(3):401–13.
[6] Protogeropoulos C, Brinkworth BJ, Marshall RH. Sizing and techno-economical optimization for hybrid solar photovoltaic/wind power systems with battery storage. International Journal of Energy Research 1997;21(6):465–79.

[7] Hansen U. Technological options for power generation. The Energy Journal 1998;19(2):63–87.
[8] WEC, 2004 Survey of Energy Resources, 20 ed. 2004: World Energy Council.
[9] GEC, Solar photovoltaic power generation: environmental technology database in 21st century, Osaka, Japan; 2004.
[10] Infield DG. Wind diesel design and the role of short term flywheel energy storage. Renewable Energy 1994;5(1–4):618–25.
[11] Wichert B. PV-diesel hybrid energy systems for remote area power generation—a review of current practice and future developments. Renewable and Sustainable Energy Reviews 1997;1(3):209–28.
[12] Dufo-Lopez R, Bernal-Agustin JL. Design and control strategies of PV-diesel systems using genetic algorithms. Solar Energy 2005;79(1):33–46.
[13] Fortunato B, Mummolo G, Cavallera G. Economic optimisation of a wind power plant for isolated locations. Solar Energy 1997;60(6):347–58.
[14] Raja IA, Abro RS. Solar and wind energy potential and utilization in Pakistan. Renewable Energy 1994;5(1–4):583–6.
[15] Lipman NH. Overview of wind/diesel systems. Renewable Energy 1994;5(1–4):595–617.
[16] Lundsager P, Bindner H. A simple, robust & reliable wind diesel concept for remote power supply. Renewable Energy 1994;5(1–4):626–30.
[17] Woodell MI, Schupp BW. The role of pilot projects and public acceptance in developing wireless power transmission as an enabling technology for space solar power systems. Solar Energy 1996;56(1): 41–51.
[18] Yu H, Pan J, Xiang A. A multi-function grid-connected PV system with reactive power compensation for the grid. Solar Energy 2005;79(1):101–6.
[19] Celik AN. Optimisation and techno-economic analysis of autonomous photovoltaic-wind hybrid energy systems in comparison to single photovoltaic and wind systems. Energy Conversion and Management 2002;43(18):2453–68.
[20] Turcotte D, Sheriff F. PV Horizon: workshop on photovoltaic hybrid systems—summary and conclusions of the workshop. Montreal, Canada, 10 September 2001.
[21] KMUTT. Clean energy hybrid systems for National Parks and Wildlife Sanctuaries in Thailand. Final Report to the National Energy Policy Office, Thailand; 2000.
[22] Boonbumroong U, Suwannakum T, Tei S. Five year's experience (1998–2003) with operation and management of PV/diesel hybrid system in a wildlife sanctuary in Thailand. In: International PVSEC-14 Conference. Bangkok, Thailand, 26–30 January 2004.
[23] Ashari M, Nayar CV, Keerthipala WWL. Optimum operation strategy and economic analysis of a photovoltaic-diesel-battery-mains hybrid uninterruptible power supply. Renewable Energy 2001;22(1–3): 247–54.
[24] Suwannakum T, Boonbumrung U, Tei S. Techno-economic assessment of PV/wind/diesel remote area power system installations at two national parks in Thailand. In: International PVSEC-14 Conference. Bangkok, Thailand, 26–30 January 2004.
[25] KMUTT, Mini-grid for rural electrification from hybrid systems (case of Kohjig Island). Proposal submitted to the Energy Policy and Planning Office, Thailand; 2003.
[26] Markvart T. Sizing of hybrid photovoltaic-wind energy systems. Solar Energy 1996;57(4):277–81.
[27] El-Hefnawi SH. Photovoltaic diesel-generator hybrid power system sizing. Renewable Energy 1998;13(1): 33–40.
[28] Celik AN. Techno-economic analysis of autonomous PV-wind hybrid energy systems using different sizing methods. Energy Conversion and Management 2003;44(12):1951–68.
[29] Seeling-Hochmuth GC. A combined optimisation concept for the design and operation strategy of hybrid-PV energy systems. Solar Energy 1997;61(2):77–87.
[30] Dakkak M, Hirata A, Muhida R. Operation strategy of residential centralized photovoltaic system in remote areas. Renewable Energy 2003;28(7):997–1012.
[31] Wies RW, Johnson RA, Agrawal AN. Economic analysis and environmental impacts of a PV with Diesel-battery system for remote villages. In: IEEE power engineering general meeting. Denvor, Colorado, USA, 6–10 June 2004.
[32] Khunchornyakong W. The first PV mega project in Thailand for "the right to know". In: International PVSEC-14 conference. Bangkok, Thailand, 26–30 January 2004.
[33] Kirtikara K. Lessons learnt from using PV stand-alone systems to provide a better quality of life of rural people. In: International PVSEC-14 conference. Bangkok, Thailand, 26–30 January 2004.

[34] CASE, Feasibility study on renewable energy systems for island electrification in Thailand. Provincial Electricity Authority (PEA); 2001.
[35] PEA. Feasibility study report on renewable energy electrification in remote villages. Thailand: Provincial Electricity Authority; 2005.
[36] Schmid AL, Hoffmann CAA. Replacing diesel by solar in Amazon: short-term economic feasibility of PV-diesel hybrid systems. Energy Policy 2004;32:881–98.
[37] Siripuekpong P. Wind turbine generation in Phuket. Electricity Generating Authority of Thailand; 2003.
[38] EGAT, Monthly statistical report on Power forecast. System Control and Operation Division, Electricity Generating Authority of Thailand; 2004.
[39] KMUTT, Clean energy system research activities. King Mongkut's University of Technology Thonburi; 2005.